Utah Department of Transportation

Lifecycle Cost Analysis for Class 8 Snowplow Trucks

DOT150358WK

Business Case – Final Report

Presented By

Asset Management Associates, PLLC

Contents

Executive Summary

The Utah Department of Transportation (UDOT) engaged Asset Management Associates, PLLC (AMA) to perform project number DOT150358WK, Lifecycle Cost Analysis for Class 8 Snowplow Trucks. This effort involved performing six (6) tasks that effectively focused on answering the following three (3) questions:

1. What is the optimal point for UDOT to replace its Class 8 snowplow trucks?
2. What level of snowplow truck replacement funding is needed each year to achieve a corresponding target class age over a 3, 4 or 5 year period?
3. How should UDOT address and fund the replacement or repair of the 197 Class 8 snowplow trucks that have a corrosion-prone frame design that has resulted in having 58 units currently with cracked frames?

To answer the above questions, UDOT tasked the consultants to review existing information and research, perform whatever analysis was needed, and provide UDOT with the appropriate guidance and recommendations. The information contained in the body of this report includes the results of our efforts, which are summarized below.

Unique Project Considerations

UDOT's core mission is identified as "Keeping Utah Moving." A critical aspect of this mission is the Agency's performance during snow clearance and related winter maintenance activities. In fact, overall public perception of UDOT's performance as an agency often is based on the public's satisfaction with its snow clearance efforts; when taxpayers are not satisfied with the success of such activities, they are quick to contact elected officials to voice their displeasure.

UDOT's Class 8 snowplow trucks are the Agency's primary tool for clearing snow and delivering its winter maintenance program. In fact, as currently constrained[1], this effectively is the only mission for many of these units.

As described, UDOT's Class 8 snowplow trucks effectively operate as emergency response vehicles, sharing operational roles that are much more similar to those of fire trucks, EMS vehicles and similar types of equipment than a 'typical' fleet vehicle. In such an emergency response environment, 'service failures' (the inability to perform when needed) typically are considered unacceptable, which means these units must be maintained at a high state of readiness and replaced as necessary to ensure maximum availability and technical capacity. Practically, this means that it is essential that UDOT be able to systematically replace these units, providing the UDOT the means necessary to support critical aspects of its mission.

Approach

The AMA team thoroughly reviewed available, relevant literature and research related to Class 8 snowplow trucks, DOT fleets and fleets in general. Due to the frame corrosion issues identified, we also included in our literature review a scan of information related to the impacts of change in winter maintenance practices (primarily, the increasing usage on 'wet' chemical treatments) on equipment specifications, maintenance practices, and remedial efforts for addressing corrosion.

[1] By public desire to outsource the performance of UDOT's summer maintenance activities.

From our review effort we confirmed that a lifecycle cost approach is generally considered a fleet best practice for identifying optimal targets for vehicle replacement. However, we also found that while many fleets incorporate elements of a lifecycle costing approach into their equipment replacement criteria, data quality issues, evolving vehicle specifications and the need to consider vehicle-specific information as part of the replacement analysis limits fleet reliance on lifecycle analysis alone.

Because Class 8 snowplows of the type operated by UDOT generally are found only within the greater Rocky Mountain regions, the described literature review effort found limited information specific to the target equipment. Accordingly, the AMA team determined a need for a peer outreach effort. To this end, the AMA team created an online survey consisting of 39 project-related questions that we provided to fourteen (14) entities identified as 'peers.' We received a total of thirteen (13) responses (including one from UDOT). While the information received provided no definitive answers to any project questions, it did provide meaningful context, points of comparison and supporting data for evaluating and considering the results from the Lifecycle Model. Additionally, this effort was particularly valuable in terms of documenting some broader industry trends related to state DOT winter maintenance practices and their impacts on equipment.

The AMA team devoted considerable efforts to creating the Class 8 lifecycle model. The existing UDOT fleet data was reviewed and analyzed through multiple approaches to identify the set of reporting criteria that would best support the data's use in a lifecycle model, provide the greatest predictive value, while relating the critical information needed to drive decisions in the most intuitive means possible. As identified below and described in detail in the report, the AMA team perceives that this goals was successfully achieved while acknowledging that because of data limitations and fleet condition concerns (mostly related to corrosion issues), the recommended model is based on a variation of a lifecycle model.

Using the results and recommendation from the recommended model, the AMA team performed the requested funding requirement calculations for reaching the target fleet age under 3, 4 or 5 year periods while providing UDOT a recommendation of the approach perceived to be most supportable. This information and the other key recommendations from this project are found below:

Key Recommendations

- The AMA team recommends 9 years as the replacement criteria for its Class 8 snowplow trucks, accompanied by a points-based vehicle inspection program to formally include vehicle condition assessment as an evaluative vehicle replacement consideration.
- UDOT should secure the necessary support to operationalize the 9-year replacement cycle over a 5-year term Target Funding Plan.
- UDOT should prioritize the replacement of units that have existing frame cracking issues within the recommended replacement plan. UDOT should only perform remedial repairs on these units as necessary to meet its minimum winter maintenance response capacity.

Next Steps

The AMA team's understanding is that a major constraint with executing the recommended strategy is that the Utah Legislature has line-item budget control over the amount of UDOT's annual maintenance budget that can be spent to purchase equipment, currently identified as $6.3M[2]. As described and detailed in this report, only by adhering with the recommended Class 8 snowplow replacement schedule can UDOT and the State achieve the lowest total cost for its taxpayers. Otherwise, simply restricting the funds UDOT can spend

[2] Slide 16 from UDOT-produced "Area Supervisor Workshop April 2015" PowerPoint presentation.

on new equipment will predictably increase the funds it spends in its equipment maintenance and repair budget. Most importantly, UDOT's ability to deliver on its core mission of "Keeping Utah Moving" is best supported by the recommended strategy as only by having an optimal age fleet can UDOT ensure that it has the actual capacity to deliver its winter maintenance program at the targeted levels of service.

Introduction

The Utah Department of Transportation (UDOT) engaged Asset Management Associates, PLLC (AMA) to perform project number DOT150358WK, Lifecycle Cost Analysis for Class 8 Snowplow Trucks. The scope of this project encompasses the following six (6) tasks:

1. Literature search of existing best practices of other DOTs and private companies to identify best practices for the Lifecycle analysis of Class 8 snowplow trucks, which shall include identifying:
    a. Numerous different analysis techniques and best practices,
    b. Performance metrics,
    c. Average annual repair costs,
    d. Average trade in values, and
    e. Number of years UDOT must own and use equipment to obtain optimal value of its Class 8 snowplow truck fleet.
2. Develop a funding strategy and methodology to replace the currently owned Class 8 snowplow trucks that have experienced cracked frames (approximately 197 trucks). This activity is separate from the Lifecycle analysis for the entire fleet of Class 8 snowplow trucks.
3. Develop and present strategies to UDOT management about the different identified options available so that UDOT may determine which options to adopt.
4. Develop the business case for the identified UDOT selected model using information from the current UDOT Class 8 snowplow fleet (approximately 500 trucks). This needs to include performance measures, (graphs, data, etc.), years to implement the program, funding needs and requirements, power point presentations, and other associated information that identifies the methodology of the proposed program.
5. Develop a UDOT Building Block request to be incorporated into the Central Maintenance Division's yearly request that is due July 15, 2015.
6. Recommend a strategy for how UDOT may reduce the average age of its Class 8 snowplow truck fleet from the current 10.25 years to the optimal average age as determined by the consultant's research, and to reduce the replacement age from the current 16 years to the optimal replacement age determined by the research. Include in the strategy the number of trucks, and dollar value that would need to be replaced in each year if the optimal average age is to be achieved in a) three years, b) four years, and c) five years.

A significant aspect of this project is its focus on a single type of equipment within the UDOT fleet – its Class 8 snowplow trucks. Accordingly, an appropriate starting point is to define some of the key concepts used for this document. In turn, this information will help frame the information covered in the balance of this report.

Key Concepts

Fleets

'Fleets' exist across the entire spectrum of public and private sector enterprises. While many individuals often associate the term 'fleet' within the context of self-powered vehicles (e.g., cars, pickup trucks, dump trucks, off-road machinery, etc.), the term 'fleets' actually can refer to any category of assets that share some set of capabilities and characteristics (such as a fleet of photocopiers or vending machines).

Asset Management

'Asset management' is the science of managing assets to achieve the lowest total cost of ownership, as known as the lowest 'Lifecycle cost[3]'. This involves balancing the cost of acquiring assets (see "Capital Costs') against the costs of maintaining and operating these assets (see "Operating and Maintenance Costs'). In practice, asset management uses historical information on costs and trends in equipment residual values to make predictive decisions about the most cost effective time to replace equipment.

Lifecycle

'Lifecycle' is a key concept within any discussion of asset management. As the term 'life' suggests, all assets are assumed to have a finite period for which it can efficiently and effectively operate. While an asset often is capable of operating long past this point, it does so with the expectation of increasing costs, technical obsolescence and/or reduced capacity when compared to operating newer, more capable assets for the same work. This is particular concern with assets that are used to support critical emergency functions such as snow removal.

Capital Costs

'Capital Costs' are one of the two major components that determine asset lifecycle costs. Capital Costs refer to the costs associated with purchasing assets and installing and/or modifying the unit to ensure that it is capable of performing its intended function as efficiently as possible. With some exceptions, capital costs are incurred when the asset is originally purchased and up-fitted[4] with these costs amortized over time to reflect its decreasing residual value as it ages as well as to account for the time value of money.

Operating and Maintenance Costs

'Operating and Maintenance costs' (O&M) refer to the expenses associated with operating and maintaining an asset over time. The primary components of O&M costs include the costs of preventive maintenance as well as any required repairs and fuel costs. Within the general category of O&M costs are two subcategories that warrant additional discussion and special treatment when attempting to map O&M cost trends: 1) accident repairs and 2) corrosion damage.

1. Accident repairs typically are captured as part of O&M costs. However, accident costs have little predictive value in terms of determining the optimal (lowest cost) replacement criteria. Accordingly, such costs typically are excluded when mapping O&M cost trends for the purpose of establishing replacement criteria.
2. Corrosion damage and repair costs often are reflective of the operating environment (such as highway salt/anti-icing and deicing chemical applications and snow removal functions) and localized maintenance practices (such as cleaning vehicles after snow events) rather than being of predictive value in terms of establishing class-level replacement criteria. Accordingly, while fleets should attempt to identify and capture these costs, such costs should be segregated from other O&M costs when attempting to use within a fleet replacement decision support tool.

Class 8 Snowplow Trucks

"Class 8 snowplow trucks" refers to the assets UDOT uses as its primary tool for performing winter maintenance activities. "Class 8" is a Federal Highway Administration (FHWA) defined vehicle weight class designation that refers to the equipment with a gross vehicle weight rating (GVWR) exceeding 33,001 lbs.

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[3] "Lifecycle costing" is defined by the Business Dictionary as, "The lowest cost of ownership of a fixed asset (purchase price, installation, operation, maintenance and upgrading, disposal, and other costs) during the asset's economic life." See http://www.businessdictionary.com/definition/life-cycle-costing.html#ixzz3bRz7Jjh7

[4] "Up-fitting" refers to in the installation of additional equipment and/or accessories that were not part of the equipment provided by the manufacturer but deemed necessary to perform its primary purpose.

(14969 kg)[5], which represents the largest vehicles that routinely travel the highway system. Besides the large snowplow trucks UDOT uses for improved snow/ice removal and control productivity, other Class 8 vehicles include most commercial over-the-road tractors used to pull large trailers (i.e., tractor/trailer rigs).

Availability

"Availability" refers to the time when a given equipment unit is work-ready. This is a key fleet performance measure for all fleets but particularly so for fleets that have a significant emergency response component. "Availability' typically is calculated by first defining the critical work hours (typically 24 hours, 7-days per week for fleets with an emergency function) and deducting all hours when units are unavailable for work due to maintenance and repairs needs. The product of these calculations usually is expressed as a percentage. The higher the level of overall equipment class availability, the fewer 'spares' are needed to accomplish a given amount of work.

Spares

"Spares" are vehicles or equipment used to substitute for the primary fleet units when those units are unavailable for work due to maintenance or repair needs. Spare units typically consist of older, less capable assets, many of which often have exceeded the optimal replacement point but are still used while awaiting funding availability before being removed from the fleet. Typically, spare units have much lower levels of availability than the primary fleet due to the impacts of age and wear. Accordingly, the older the fleet, the higher the spare ratio needed to ensure the adequate availability of work-ready units. Conversely, 'spares' absorb a disproportionate level of maintenance resources (due to increased maintenance and repair needs) that when spread over declining levels of utilization, result in ever-increasing costs per mile or year.

Minimizing Lifecycle Costs

Figure 1: Asset Lifecycle Cost Example[6] graphically illustrates the concept of identifying the minimal asset lifecycle costs range. It consists of three curves: 1) a capital costs curve, 2) a maintenance and operating costs curve, and 3) a "total asset cost curve" that combines the above costs.

Figure 1: Asset Lifecycle Cost Example

[5] See http://www.afdc.energy.gov/data/10380

[6] From "Modeling Equipment Costs," a presentation by Dr. John Hildreth of UNC-Charlotte to the EMTSP annual conference on June 12, 2012 in Orlando, FL. Reproduced with permission by the author.

Within the context of the above figure, the ideal replacement for units with these cost characteristics would be anywhere in the green area (the 15,000 - 21,500 hour range). Conversely, operating these assets beyond approximately 21,500 hours (in the yellow, orange and red areas) would result in increasing the total cost of ownership for these units.

Note 1: In the above example, 'hours worked' is the unit cost measure used to track lifecycle ownership costs. However, other unit measures, such as miles operated or age also may be used, based on the data available and the measure's appropriateness to the asset being examined.

Note 2: Figure 1: Asset Lifecycle Cost Example is intended to represent the costs for an entire class of assets rather than a single asset. Additionally, while the above figure indicates that operating cost increases are fairly linear, increasing slowly and steadily over time, in reality (and especially when considering individual assets), major costs such as replacing an engine or transmission occur irregularly and with limited predictability. Accordingly, while the above discussion is related to identifying a target set of replacement criteria for a given class of assets, it is practically impossible to identify the specific point which a given unit should be replaced to avoid a major, costly failure. Accordingly, while the application of asset management principles generally is considered best practice for fleet asset management, its power is statistically based and tends to work across a fleet of assets and over time rather than driving the appropriate action for a specific asset (a 'sell or keep' decision).

As the above figure illustrates, "owning" costs (capital costs) tend to dominate total asset costs during the early periods of having and using an asset. However, maintenance and operating costs dominate the later years/period of use. Factors that cause O&M costs to rise over time include the increased frequency of maintenance and repairs needed as well as increased complexity of these services. This results in reduced equipment availability to perform work as it ages/wears, which reduces 'utilization' (which effectively represents the denominator in a units cost calculation while 'costs' represent the numerator). An additional factor that leads to decreased utilization over time (and increasing rates of O&M costs) is the natural tendency for employees to prefer to operate newer equipment over older units for reasons that include greater comfort, better reliability and superior performance (among others). In combination, the factors support an overall trend of increasing O&M costs over time as due to the dual impacts of increased costs and decreasing utilization.

Literature Review

As previously indicated, the literature review task for this project is described as capturing, "existing best practices of other DOTs and private companies to identify best practices for the Lifecycle analysis of Class 8 snowplow trucks, which shall include identifying:

A. Numerous different analysis techniques and best practices,

B. Performance metrics,

C. Average annual repair costs,

D. Average trade in values, and

E. Number of years UDOT must own and use equipment to obtain optimal value of its Class 8 snowplow truck fleet."

This document section contains a synopsis of our findings from the literature review effort to determine what lessons and/or other insights can be applied to UDOT's Class 8 snowplow truck fleet. A separate section describes the results of our survey of peer entities on their Class 8 snowplow unit fleet and related winter roadway maintenance practices.

Appendix A: Literature Review Citations identifies the primary resources reviewed by the AMA consultants for this project. As indicated, these resources are categorized as follows:

1. Studies on State DOT Equipment Replacement and Funding Practices
2. Studies on Fleet Replacement Decision Support Tools
3. Reports on Industry Practice
4. Reports on Corrosion Prevention Practices

The primary subject matter of this study – determining optimal replacement criteria for UDOT's Class 8 snowplow trucks – is a specialized topic within the general topic of fleet replacement strategies and methodologies. The resources identified under categories 1-3 from the above list primarily relate to this topic.

The literature review category "Reports on Corrosion Prevention Practices" refers to recent studies and presentations on the topic of the equipment corrosion related to the use of various roadway deicer products. This information also includes research on maintenance practices and protective treatments related to preventing or mitigating these impacts. As such, the AMA consultants included and reviewed this material for its potential relevance to the corrosion-related issues identified by UDOT as part the 'frame-cracking' issue (item 2 from the project's scope of work).

NCHRP Synthesis 452

Of particular relevance and value to this project is a 2014 study, – National Cooperative Highway Research Program (NCHRP) Synthesis 452, "State Department of Transportation Fleet Replacement Management Practices," that was published by the Transportation Research Board (TRB). This report describes the current state of the practice regarding fleet replacement management and financing methods by state departments of transportation. It also includes a discussion of the perceived strengths and weaknesses of different management and financing methods. Importantly, this report included the results of a survey of equipment replacement and funding practices at State DOTs, with 38 of the 50 state DOTs responding.

Findings from Synthesis 452 perceived to be of specific relevance to this project include the following:

A. The State DOTs responding to the survey mostly use one of the following six methods for planning asset replacements:

   1. Replacement cycle policies based on formal analysis of Lifecycle costs (as described in the "Minimizing Lifecycle Costs" section of this document);
   2. Replacement cycle policies based on judgment, experience, rules of thumb, etc. (effectively, a more suggestive approach to attempting to operationalize a Lifecycle costing model);
   3. Multiyear fleet replacement plans showing future replacement dates and costs by asset;
   4. Replacement lists that identify assets meeting pre-defined criteria (e.g., age or mileage);
   5. Methods for prioritizing specific assets for replacement when funds are insufficient to replace every asset that should be replaced; and
   6. Repair versus replace tools or policies that target specific assets needing expensive repairs.

   Each of above methods was considered by at least one DOT that responded to the survey to be either "the most important" or "second most important" method for guiding replacement decisions. As a result, there was no consensus by state DOT respondents at to which decision support method was considered most effective.

   In general, NCHRP Synthesis 452 indicated that the use of structured replacement methods that take into account such factors as the age and condition of individual assets and the operational needs of fleet user organizations produce better and more defensible results than replacement methods that relied more on historical practices. The disadvantage of structured replacement tools is the extent to which they may require specialized skills in coding and capturing data, as well as the analysis of such data and the development of forecasts, cost and performance metrics, etc.

B. The state DOTs providing responses mostly were not funding their equipment replacement programs sufficiently to support their stated replacement criteria.

C. 60% of the state DOT respondents indicated that the timely replacement of fleet assets was not a high priority for their governor, state budget office, and/or legislature, and 30% that decision making is decentralized and beyond their control.

D. The document includes multiple reference to studies that repeatedly show that old fleets have greater lifecycle costs than younger fleets

In combination, the above findings suggest that UDOT's Class 8 snowplow truck funding difficulties are not unique; however, for UDOT to achieve its core mission of "Keeping Utah Moving," it remains incumbent on UDOT to ensure that the Agency has the necessary work-ready resources to accomplish this goal.

Studies on Fleet Replacement Decision Support Tools

As identified in Appendix A: Literature Review Citations, the AMA consultants found seven (7) resources to be especially relevant to the subject of identifying an appropriate fleet replacement support tool for UDOT. Unsurprisingly, five (5) of the seven (7) resources were reports, papers or studies sponsored by state DOTs with the purpose of identifying and recommending a replacement methodology for one or multiple categories of state DOT equipment. Additionally, the following presentations were considered particularly valuable in terms of presenting the entire topic of fleet replacement planning within a presentation format that was especially straightforward and understandable by non-fleet personnel:

1. "Fleet Age Planning," a presentation by Dr. Mike Vorster at the 2012 National Equipment Fleet Management Conference, and

2. “Modeling Equipment Costs,” a presentation by Dr. John Hildreth, also presented at the same conference.

With respect to the five (5) state DOT-sponsored decision support studies and the two presentations, the AMA consultants note that all these resources generally were consistent in using some variation of a Lifecycle cost methodology within the constraints of the client’s data (both in terms of quality and reliability). In fact, a significant focus of each of the DOT-sponsored studies tended to involve the treatment of data, mostly in regards to data-cleansing approaches and the treatment of outliers. The AMA consultants note that the complexity of addressing ‘bad’ data (“bad” referring to missing or inaccurate data) along with the enormous volume of data that is typical of a DOT fleet are major challenges in large fleet engagements and often significantly influences the replacement approach recommended to the client.

With respect to the data availability and quality concerns associated with using any replacement support tool, the AMA consultants found a 2008 study sponsored by the Oregon DOT to be exceptionally valuable. This study, titled “Equipment Replacement at DOTs: Prioritization Measures, Software Tools, and Supplementary Data” is especially noteworthy in terms of its use of sensitivity analysis as part of its modeling efforts. The following table (duplicated from the source document) describes these criteria and how they were analyzed[7]:

Table 1: Replacement Priority Measures Evaluated

Replacement Prioritization Measure	Explanation
1. Replace random first Vehicles are selected randomly for replacement.	Control measure
2. Replace oldest first	Active equipment units are ranked based on the time they have spent as active fleet members.
3. Replace highest Life to Date[8] (LTD) usage first	Active equipment units are ranked based on the accumulated miles they have traveled during the time spent as active fleet members.
4. Replace highest (LTD repair cost + LTD operating cost) first	Active equipment units are ranked based on the accumulated repair and operating cost they have incurred during the time spent as active fleet members.
5. Replace highest (LTD repair cost + LTD operating cost + LTD fixed cost) first	Active equipment units are ranked based on the accumulated total cost they have incurred during the time spent as active fleet members.
6. Replace highest (age/age standard) + (LTD usage/use standard) first	Active equipment units are ranked based on the sum of ratios computed using age and use standards.
7. Replace highest (age/age standard) + (LTD usage/use standard) + (LTD total cost/acquisition cost) first	Active equipment units are ranked based on the sum of ratios computed using age, cost, and use standards.
8. Replace highest (repair cost for present year – repair cost for prior year) first	Active equipment units are ranked based on the highest positive difference between repair cost incurred during the current year and the preceding year.
9. Replace highest (total cost for present year – total cost for prior year) first	Active equipment units are ranked based on the highest positive difference between total cost incurred during the current year and the preceding year.
10. Replace highest (LTD repair cost + LTD operating cost)/LTD usage first	Active equipment units are ranked based on the accumulated operating and repair cost per mile computed for the time units have spent as active fleet members.

Note 3: Measures 6 and 7 utilize fixed age and use standards as part of the measure.

[7] Kriett, P.O., W.N. Mbugua, D.S. Kim, and J.D. Porter, “Equipment Replacement at Departments of Transportation: Prioritization Measures, Software Tools, and Supplementary Data,” Transportation Research Record: Journal of the Transportation Research Board, No. 2150, Transportation Research Board of the National Academies, Washington, D.C., 2010, p. 7

[8] “Life to date” is the accumulated data for usage, repair costs, fixed costs, operating costs, and acquisition costs.

The key findings from this analysis were as follows:

> "Prioritization measure 2 (i.e., replace the oldest first) was found in the best set for six of the ten combinations of budget and equipment class. It is also the top ranked measure (based on lowest cost/mile) for five of the ten combinations. Prioritization measures 4, 5, 6, and 8 are found in the best set in five of the ten combinations.
>
> Measures 7 and 10 are found in the best set in four of the ten combinations. Measure 9 is found once in a best set.
>
> Prioritization measure 2 (replace the oldest first) appears to be the overall most effective measure. Differences in cost per mile between the least and most effective prioritization measures ranged from $0.007 per mile for sedans to $0.06 per mile for heavy diesel trucks resulting in annual cost differences of $12K to $350K per year between the worst and best priority ranking measures[9]."

As the above research indicates, equipment age tends to have the greatest sensitivity (is the most powerful predictor) in terms of identifying equipment replacement priorities to achieve the lowest lifecycle cost. That said, the described results also indicate that the other criteria have varying degrees of merit for consideration in a replacement planning model; however, the ability to leverage those additional inputs for improving the prediction accuracy for optimal Lifecycle costing is much more dependent on the availability and accuracy of equipment cost data.

Corrosion Research

The AMA team identified four resources on the topic of equipment corrosion that we considered to be highly relevant to this project. These are related documents, built on research originally performed by the Western Transportation Institute at Montana State University for the Washington State DOT (WSDOT). The latest of these resources, "Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment used by Transportation Agencies for Snow and Ice Control[10]" was published by the Minnesota Department of Transportation in April 2015 and intended to serve as an overall reference guide to understanding the causes, effects and treatment options equipment corrosion related to snow and ice control. While the details of this and the other referenced documents are sufficiently complex as to extend beyond what can reasonably be recapped in this document, the following are some of the key themes from these resources:

- The widespread use of wet-type chemical treatments for winter roadway maintenance has significantly increased equipment corrosion damages. Based on an DOT fleet survey, these impacts are estimated by researchers as follows[11]:
  - 17.3% depreciation in equipment value
  - 8.5% in increased equipment downtime
  - 11.9% in reduced equipment reliability
  - 17.3% in reduced equipment service life
  - 19.6% in increased premature repair and replacement
  - 1.5% reduced safety, due to faulty parts on equipment
- The available roadway treatment chemicals differ significantly in terms of potential corrosion impact on vehicles. However, these differences typically are considered secondary (or not considered at all)

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[9] Ibid, page 8.
[10] Nazari, M., Bergner, D., Shi, X., "Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment used by Transportation Agencies for Snow and Ice Control", Western Transportation Institute, Montana State University, April 2015.
[11] Ibid, page 24.

by maintenance forces when compared to cost and perceived effectiveness of the roadway treatment material chosen.

- Changes to equipment specifications have reduced (but not eliminated) some of the more critical corrosion-related problems. These changes include the following:
    - Changing truck specifications to single truck frame rails (as UDOT has done);
    - Moving critical electrical junction boxes to within the truck cab to reduce exposure to the elements and, particularly, to roadway treatment chemicals;
    - Specifying that all exposed (out of the truck cab) junction boxes be filled with water-resistant grease;
    - Use of stainless steel, galvanized metal and/or plastic in place of traditional steel for increased corrosion resistance;
    - Exploring the use of various vehicle anti-rust and chemical neutralizing treatments to prevent or reduce corrosion damage.
- Revising operator equipment maintenance instructions to include more stringent cleaning of vehicles after roadway treatment chemical application.

Equipment Management Technical Services Program

Another resource identified as part of our literature review effort was the information available through the American Association of State Highway Transportation Officials (AASHTO) Equipment Management Technical Services Program (EMTSP)[12]. The EMTSP program is sponsored through specific contributions of individual AASHTO member states and targets the support needs of state DOT fleets through participation in the various AASHTO regional fleet organizations as well as service as a clearinghouse for fleet best practice information.

Of particular relevance to this project are the set of Fleet Performance Metrics developed through the efforts of the AASHTO EMTSP. On November 16, 2012, the AASHTO Subcommittee on Highways (SCOH) approved AASHTO resolution 12-03 Fleet Performance Measures. This resolution endorsed the use of the key performance metrics for equipment fleet of utilization, preventive maintenance, retention (fleet replacement backlog), and availability/downtime. Each State fleet is encouraged to implement the four (4) Performance Measures and share their results via National Performance Metrics portal on the ETMSP website.

The performance reporting provided is not intended to compare states against one another as each state self-determines how to compile the individual measurements. Instead, the reporting is intended to allow each reporting state to benchmark its current status and track future actions. Currently, UDOT is one of 22 state DOTs providing some level of fleet performance reporting.

Snowplow Fleet Survey

The AMA team notes that our literature review identified little research information that that was specific to Class 8 snowplow trucks. We anticipated this result as the number of entities that operate Class 8 snowplow trucks is quite small, particularly when considering the additional operational and environmental factors in which UDOT operates its Class 8 snowplow fleet. Accordingly, the AMA team determined that to address

[12] The EMTP website is found at the following link: http://www.emtsp.org.

the desired benchmarking needs of this project, we would need to conduct outreach to entities determined to be UDOT peers. To this purpose, the AMA team prepared a survey tool that was designed to collect as much relevant information as respondents could reasonably be expected to provide without discouraging survey completion. These 'peers' consisted of fourteen (14) entities: eleven (11) state DOTs, two (2) cities and one (1) county. While Class 8 snowplow trucks are the core focus of this project, Class 7 snowplow trucks were included in the survey as a strategy for ensuring an adequate volume of relevant responses. However, because we received sufficient Class 8 snowplow truck information, the Class 7 data provide to be of supplemental value only.

AMA released the forty-four (44) question survey to the fourteen (14) entities targeted by the survey on May 13, 2015. All respondents that completed the survey were promised a copy of the results in exchange for their participation. The survey was closed on May 31, 2015 after receiving thirteen (13) responses including all the targeted state DOTs, the City of Salt Lake, Utah and UDOT. Subsequent to closing the base survey, the AMA team separately emailed survey respondents an additional question about the demographics of the actual Class 8 snowplow trucks actually replaced (as opposed to the stated replacement criteria). The information gathered through this additional outreach was manually captured as an addition to the existing survey responses.

The full text of the survey and all responses are contained in both an EXCEL-based spreadsheet and a PDF titled, "Class 8 Snowplow survey-final."

Question-by-Question Summary

The survey design included thirteen (13) screens. The first screen contained introductory material while the second screen contained five (5) questions related to collecting respondent information and permissions to share respondent and organization details as well as asking whether the respondent wished to receive a copy of the survey (all did). Screens 3-13 contained the remaining 39 questions (starting with question 6), the results of which as summarized below:

Screen 3: Demographics of Heavy Duty Snowplow Fleets

Question 6: Approximately how many Class 8 dump trucks do you have and use as snowplow units?

- 4,767 Class 8 snowplow trucks were reported on by the 13 respondents. The Class 8 snowplow truck fleet size ranged from a high of 792 units (California Department of Transportation) to a low of 157 (Arizona Department of Transportation).

Question 7: Of the Class 8 snowplows identified above, approximately how many use the following types of plows?

- 2,911 (61.1%) of the units were configured with single wing plows
- 1,360 (28.5%) of the units were configured with only the standard front mounted snowplows
- 373 (7.8%) trucks were configured to apply liquid chemical deicing/anti-icing
- 89 (1.9%) of the units were configured with dual wing plows
- 34 (0.7%) were configured to be used with tow plows.

Question 8: Approximately how many Class 7 dump trucks do you have and use as snowplow units?

- 1,101 Class 7 snowplow trucks were reported on by the 13 respondents. Class 7 snowplow truck fleet size ranged from a high of 303 (Colorado Department of Transportation) to 2 units (New Mexico Department of Transportation).

Question 9: **Of the Class 7 snowplow identified above, approximately how many use the following types of plows?**

- 619 (56.3%) units were configured with only the standard front mounted snowplows.
- 366 (33.2%) of the units were configured with single wing plows,
- 115 (10.4%) were configured to apply liquid chemical deicing/anti-icing products only.
- 1 (0.1%) was configured with dual wing plows,
- No units were configured to be used with tow plows.

Screen 4: Snowplow Fleet Replacement Criteria – Class 8

Question 10: **What replacement criteria are you using for your Class 8 snowplow trucks (e.g., X years and/or Y miles or Z hours, etc.)?**

- 12 fleets (92%) reported that their planned replacement criteria for Class 8 snowplow trucks are calculated using the elements of age and elapsed miles
- Five (5) of the 12 fleets added accumulated repair cost to the age and mileage criteria.
- One (1) of the 12 fleets used a combination of age and elapsed engine hours (Washington DOT).
- One (1) of the 12 fleets reported using age only (Utah DOT)
  Note 4: During project interviews, UDOT personnel indicated that vehicle condition also was considered when prioritizing specific units for replacement.

Class 8 snowplow truck replacement criteria ranged from 10 years, 175-250K miles and a percentage of life-to-date repairs to purchase cost (a three (3) criteria standard used by the California Department of Transportation) to 23 years, 350,000 miles and a percentage of life-to-date repairs to purchase cost (also a three (3) criteria standard used by the Montana Department of Transportation).

Question 11: **What is the current actual average age/miles/hours for your Class 8 snowplow trucks?**

- This question was replaced by the supplemental question identified below as question 45. This is because the 'average age/miles' information requested by this question was determined to have little research value. However, the responses to this and all other question are identified in the survey response details.

Questions 12: **What replacement criteria are you using for your conventional (non-snowplow) Class 8 dump trucks (e.g., X years and/or Y miles or Z hours, etc.)?**

- Questions 12, 13, 16 and 17 were included in the survey in case of an insufficient peer entity response ratio and/or a low population of Class 8 snowplow units operated by peer entities. However, a high survey response ratio and the large volume of respondents operating equipment of the type targeted by this project made these questions superfluous.

Question 13: **What is the current actual average age/miles/hours for your conventional (non-snowplow) Class 8 dump trucks?**

- See question 12 comments.

Screen 5: Snowplow Fleet Replacement Criteria – Class 7

Question 14: What replacement criteria are you using for your Class 7 snowplow trucks (e.g., X years and/or Y miles or Z hours, etc.)?

- 11 fleets (85%) reported that their planned replacement criteria for Class 7 snowplow trucks are calculated using the elements of age and elapsed miles
- Five (5) of the 11 fleets added accumulated repair cost to the age and mileage criteria.
- One (1) of the 11 fleets reports using age and elapsed engine hours (Washington DOT)
- One (1) of the 11 fleets reports using age only (Utah DOT)
  Note 5: During project interviews, UDOT personnel indicated that vehicle condition also was considered when prioritizing specific units for replacement.

Class 7 snowplow truck replacement criteria ranged from 8 years/175,000 miles (New Mexico Department of Transportation) to 23 years/350,000 miles (and a percentage of repair costs - Montana Department of Transportation).

Question 15: What is the current actual average age/miles/hours for your Class 7 snowplow trucks?

- As indicated in question 11, we determined that the 'average age/miles' information requested by this question was determined to have little research value.

Questions 16: What replacement criteria are you using for your conventional (non-snowplow) Class 7 dump trucks (e.g., X years and/or Y miles or Z hours, etc.)?

- See question 12 comments.

Question 17: What is the current actual average age/miles/hours for your conventional (non-snowplow) Class 7 dump trucks?

- See question 12 comments.

Screen 6: Winter Roadway Treatment Material Usage

Twelve (12) respondents (92%) completed this section. Questions and responses are summarized below:

Question 18: Has your agency changed its approach towards its selection of winter roadway treatment material in the last few years (e.g., moved from the use of abrasives – sand, fly ash, cinders, etc. – to brine pre-treatment and/or chemical deicers)?

- Yes – Eight (8) respondents
- No - Four (4) respondents

Question 19: If your Agency changed winter roadway treatment material usage, when and why did it change?

- Movement from abrasives to granular/liquid chemicals due to their (the latter's) effectiveness in colder temperatures. – Last 3-7 years
- Granular/liquid chemicals provide increased highway safety and levels of service, competitive costs and less post-storm clean-up activities. – Last 3-7 years

Questions 20: Which if the following types of winter roadway treatment materials does your agency currently use?

- Salt was the primary treatment selected
- Magnesium Chloride, Redmond Materials Salt/Ice Slicer ® and brine followed in close order

Question 21: **With respect to the materials identified in the prior question, please rank these materials in terms of usage from greatest (most - 1) usage to least (least - 6) used by your Agency?**

- See response to Question 20

Screen 7: Snow Material Treatment Impacts on Vehicle Condition

Twelve (12) respondents (92%) completed this section. Questions and responses are summarized below:

Question 22: **Have you noted any specific impact on vehicle condition (e.g., increase in corrosion, decrease in service live, etc.) associated with the currently used winter roadway treatment materials?**

- Yes – Eleven (11) fleets
- No – One (1) fleet

Question 23: **Does there seem to be any specific vehicle condition impact pattern (e.g., additional corrosion, electrical wiring and/or brake component problems, etc.) associated with of using the different types of winter roadway treatment materials? If so, please describe the differing impacts by material type.**

- Yes – Ten (10) fleets
- No – Two (2) fleets

Fleets reporting a negative truck condition impact associated with the use of particular winter roadway treatment materials the consensus was that the use of magnesium chloride followed by Redmond Material Salt/Ice Slicer ® were the most problematic.

Question 24: **At what level (if any) do the relative impacts of the different winter roadway treatment materials on vehicle maintenance and/or useful life become a decision factor in what materials the maintenance forces use?**

- Yes – consideration is given - One (1) fleet
- No – consideration is not given - Eleven (11) fleets

Screen 8: Mitigating the impact of Winter Roadway Treatment Materials on Snowplow Vehicles

Twelve (12) respondents (92%) completed this section. Questions and responses are summarized below:

Question 25: **Do you have formal Snowplow truck operator training requirements? If so, is there a provision for repeating this training periodically?**

- Yes - Ten (10) fleets indicated that they have formal training requirements and have provisions for repeating that training.
- No – Two (2) fleets

Question 26: **What steps has you agency taken in terms of it vehicle maintenance practices (including operator instructions) to mitigate these impacts?**

- Ten (10) respondents indicated that their organization had implemented some combination of post-storm washing policies, increased the use of neutralizing chemicals and soaps, coatings, and increased PM cycles.
- One (1) fleet did not provide a response
- One (1) fleet responded "unknown"

Question 27: **To what extent are the above steps/policies being followed?**

- Seven (7) fleets responded that their prescribed steps/polices were being followed

- Four (4) fleets responded that their prescribed steps/polices were being followed about 50% of the time
- One (1) fleet responded that they did not know

Question 28: How effective have these steps been in mitigating any negative impacts of roadway treatment materials on snowplow trucks?

- Ten (10) fleets responded that their selected steps taken were generally effective
- One (1) fleet responded that their experience was negative
- One (1) fleet responded that they did not known

Question 29: What change(s) have had the greatest positive impact?

- Ten 10 fleets responded stated that the washing of trucks after storm events was the most proactive approach.

Question 30: What change(s) did not work?

- Four (4) fleets responded agreed that all changes had successes in various degrees.
- Four (4) fleets responded that at least one of their changes did not work
- Four (4) fleets responded that they did not know

Question 31: Does your Agency use undercarriage wash racks? If so, at roughly what percentage of your truck staging location (shops or maintenance facilities) are these wash racks available?

- Yes – Three (3) fleets
- No – Nine (9) fleets

Of the three (3) fleets responding that they own undercarriage wash racks, they quantified their availability as follows:

- Yes/ 100% (Salt Lake City, Utah}
- In FY15 we built six new truck washes, and over the next two FY's we'll construct 12 more. (Arizona DOT)
- Have 2-3 in larger cities. Most stations use fire hoses and pressure washers (South Dakota)

Screen 9: Equipment Specification Changes

Twelve (12) fleets responded (92%) completed this section. Questions and responses are summarized below:

Question 32: What kinds of changes (if any) have you made in vehicle purchasing specifications (e.g., chassis design, dump bed composition, application of rust preventative, etc.) have you made to mitigate these impacts?

- Of the 12 fleets responding the most common specification changes were in the areas of utilizing more stainless steel bodies and spreaders, upgraded wiring workmanship requirements and defining the mounting locations of electrical junction boxes.

Question 33: How effective have the changes identified in the prior question been in addressing these problems?

- Yes - Positive Outcome – Eleven (11) fleets
- No – Negative Outcomes – Zero (0) fleet
- Unknown – One (1) fleet

Question 34: What change(s) have had the greatest positive impact?

- Of the 11 fleets responding positive outcomes, the most common specification changes identified were:
  - Stainless steel bodies and material spreaders (South Dakota)
  - Chemical barrier wiring connectors and harness plugs and composite engine oil pans (Arizona DOT)
  - Moving electrical components into cab (Washington DOT)
  - Changes to the external electrical wiring (Oregon DOT)
  - The single parent rail has worked good so far (Utah DOT)

Question 35: What change(s) did not work?

- Four (4) of the 12) fleets provided the following comments:
  - Coatings. We tried powder coating and special paints. None have proven worth the additional costs. (Idaho DOT)
  - Powder coat (Colorado DOT)
  - Stainless bodies just moved the rust to the chassis. (Oregon DOT)
  - Ignoring the issues (Montana DOT)

Question 36: Have you changed your Class 7 or 8 dump truck replacement criteria within the last 10 years?

- Yes – Seven (7) fleets
- No - Five (5) fleets

Question 37: If your response to the prior questions is 'yes,' was the impact of the new winter roadway treatment and practices on vehicle condition a significant factor in that change?

- Yes – Four (4) fleets
- No – Three (3) fleets

Question 38: If your response was 'no', do you anticipate needing to change your replacement criteria for the Class 7 and 8 dump truck/snowplow fleet to address the new winter roadway treatment materials?

- Yes – Two (2) fleets
- No - Three (3) fleets

Question 39: What change(s) would you hope to make in your existing snowplow replacement criteria if possible (e.g., replace in X years versus current Y criteria)?

- Reduce replacement criteria – Seven (7) fleets
- Increase replacement criteria – Two (2) fleets
- Retain current replacement criteria – One (1) fleet
- Unknown – Two (2) fleets

Impact of Winter Roadway Treatment Materials on Snowplow Truck Residual Values

Twelve (12) respondents (92%) completed this section. Questions and responses are summarized below:

Question 40: What impact on equipment end-of-life residual values has the change in snow treatment materials had on your Class 7 or 8 dump fleet (e.g., average vehicle value at auction has increased/decrease X%)?

- Increased value – Two (2) fleets
- Decreased value – Three (3) fleets
- Unchanged – Two (2) fleets

- Unknown - Five (5) fleets

Additional Fleet Questions (Optional)

Twelve (12) respondents (92%) completed this section. Questions and responses are summarized below:

Question 41: Does your organization have any snowplow trucks in its fleet that have a 'nested 'C'-style' frame design?

- Yes – Seven (7) fleets
- No – Three (3) fleets
- Unknown – Two (2) fleets

Question 42: Has your organization experienced any problems with cracked frames on its Class 8 or Class 7 snowplow trucks?

- Yes – Five (5) fleets
- No – Seven (7) fleets

Question 43: Has your organization noted any correlation between the type of plow devises used and any frame problems?

- Yes – One (1) fleet
- No - Eleven (11) fleets

Question 44: Have you changed the color of your new snowplow trucks in the last 10 years to improve resale value? If so, what color are you using now?

- Yes – Four (4) fleets
- No – Eight (8) Fleets

Of the 4 fleets responding that they had changed snowplow truck colors, the most common color selected was white and factory standard yellow.

Question 45: Supplemental Question (collected outside the survey via emails and phone calls: Of the Class 8 snowplow trucks that you actually have replaced in the last couple of years, what is the average age, mileage and/or hours on these units at the time they were sold or disposed?

- Eleven (11) respondents answered this question. Responses ranged from a low of 13 years old / 79,796 Miles (City of Salt Lake) to a high of 24 Years / 313,000 Miles. The average accumulated age and mileage for the 11 responding fleets was 16.7 years of age and 222,893 miles.

Key Points

As described above, the peer survey effort provided no definitive answers to any project questions but it did provide meaningful context, points of comparison and supporting data for evaluating and considering the results from the Lifecycle Model. In fact, the peer survey was particularly valuable in terms of documenting some broader industry trends in terms of the use of winter maintenance practices and their impacts on equipment.

Frame Issues

Item 2 of this Project's scope of work states the following:

> "Develop a funding strategy and methodology to replace the currently owned Class 8 snowplow trucks that have experienced cracked frames. This activity is separate from the Lifecycle analysis for the entire fleet of Class 8 snowplow trucks. (Approx. 197trucks)"

Our initial conversations with UDOT personnel included probing into the suspected causes of this frame cracking problem and understanding what actions have been taken (or need to be taken) to prevent this issue from expanding into the balance of the Class 8 snowplow truck fleet and/or other equipment. During these communications, UDOT personnel indicated that their research and discussions with the vehicle Original Equipment Manufacturers (OEMs) and peer fleets suggested that the primary cause of the frame cracking was associated with the corrosion created by deicer materials being trapped between the frame rail channels on units equipped with what is described as double or "nested C-channel frame rails". UDOT further indicated that they addressed this problem effectively and it had been resolved by a 2003 equipment specification change that required manufacturers to use a single member frame design (reducing the opportunity for roadway treatment chemicals to be trapped in inaccessible areas of the vehicle). This UDOT specification change mirrored a trend at other DOTs to a single frame rail design for similar reasons, a change that subsequently was confirmed as a recommended corrosion reduction practice in the literature search. However, given that 197 Class 8 snowplow vehicles with the problematic frame design remain in the UDOT fleet, the AMA team proceeded to review this issue in order to recommend a strategy and methodology for UDOT to address existing vehicles.

As indicated, UDOT still owns 197 Class 8 snowplow trucks with the problematic frame design. However, only around 58 (29%) of these vehicle vehicles have thus far manifested frame cracking. That said, the fact that 29% of these vehicles already have demonstrated such problems (compared to few such problems on the single frame units), suggests an urgent need to address this concern.

The following are some basic facts about the truck frames, the units in question and the identified options for addressing these problems:

- Frame rails for heavy-duty vehicle are made of tempered steel and are specific to vehicle make, model and year.

- OEMs do not inventory frame rails for non-current vehicle models as most vehicles requiring a frame replacement are sufficiently damaged as to be consider a 'total loss.' This is particularly true for Class 8 vehicles (due to the relatively low production volumes for these vehicles and the amount of client-specific specifications typical of this vehicle class).

- OEMs can provide replacement frame rails but doing so typically requires 60-days[13] to deliver because of the need for a special production run or special order from a supplier. Even then, the new frame rails require significant additional fabrication during installation as such 'standard' rails are not delivered with the specific frame holes, brackets, and other modifications that were performed to complete the vehicle as originally specified and configured.

- OEMs discourage significant welding or drilling on frames rails because the heat generated can impact the tempering of these items, causing significant loss of strength.

[13] Slide 14 from UDOT-produced "Area Supervisor Workshop April 2015" PowerPoint presentation.

- The age of the trucks with cracked frames ranges from 13 to 19-years[14]. The average residual value of these units currently is identified as $7,480[15].

- UDOT identifies a contracted cost of $44,738[16] (inclusive of all parts and labor) to have a vendor modify and install new frame rails on the effected trucks. After modifications, UDOT estimates that it would need to operate the repaired vehicles for an additional seven (7) years[17] to justify this investment yet it is unclear to what extent (if any) these modification would increase unit residual value[18].

- The identified alternative to the complete frame rail replacement described above is some combination of frame welding and the incorporation of additional reinforcing plates (also known as 'fish-plating") to strengthen the affected areas. However, UDOT's experience with such repairs is that they have proven to be effective for only limited duration (typically no more than two (2) years) due to the continuing impacts of rust and corrosion. Even so, UDOT's cost for such repairs averages from $10-15,000 per unit and trucks with such repairs are retained and utilized only for winter plow operations due to safety concerns.

Analysis and Recommendations

As described above, there is no scenario where either repairing or replacing truck frames makes financial sense due the low residual value of the units either pre or post repair. The superior option clearly is to provide a higher replacement priority to those units that have existing frame cracking issues, with the remaining units that have the problematic design receiving somewhat lower replacement priority (and more frequent safety inspections). Despite these statements, the AMA team notes that to meet its minimum winter maintenance response capacity, UDOT may be required to perform some number of remedial repairs on the subject units until new replacement trucks can be placed into service by UDOT.

We also note that the near-term necessity of continuing to operate units with this known problem requires UDOT to assume some additional degree of risk exposure, which is why UDOT limits the use of these units to winter plowing. Accordingly, replacing these units as quickly as feasible supports both sound fleet and risk management practices. Safety risks include the indirect result of UDOT failing to clear roadways at its target clearance rate due to equipment unavailability as well as more direct risks associated with equipment breakdowns.

With respect to the question of the number of units needed to meet its winter maintenance requirements, the AMA team notes that UDOT currently has a separate research project ongoing to examine its snowplow route assignments. Hopefully, this effort will identify options that allow UDOT to achieve its target winter maintenance performance goals with a somewhat lower number of snowplow trucks, providing an opportunity to remove the problematic units out of the fleet more quickly.

[14] From "Cracked Frames on International trucks.xlsx," a UDOT-provided file.
[15] Slide 14 from UDOT-produced "Area Supervisor Workshop April 2015" PowerPoint presentation.
[16] Ibid.
[17] Ibid.
[18] Ibid.

Lifecycle Costing Model

Overview

To assist in identifying an optimal fleet age for the UDOT snowplow fleet (and the corresponding funding needs), the AMA team created a total asset cost model for the UDOT Class 8 snowplow fleet that is based on actual UDOT fleet data. In turn, the resulting analysis from this model provides critical inputs for the performance of project Task 3 (identifying available strategies and options) and Task 4 (developing a business case). As described below, the AMA team successfully developed such a model (with the caveat noted below) and as anticipated, the information from this model provided the objective data used in interpreting the information gathered through the literature review and the peer survey efforts described elsewhere in this document.

With respect to the above statements, the AMA consultants acknowledge that the lifecycle model developed for this project and the resulting recommended replacement criteria do not reflect a 'pure' Lifecycle costing approach; rather, it reflects our adaption of such an approach to the limitations of the existing data. In particular, we note that the described frame-cracking issues associated with corrosion damage and the critical need for UDOT to aggressively replace the affected units was a significant factor in framing our overall recommendations.

UDOT Fleet Maintenance Cost Data

Clearly, UDOT has attempted to be a careful steward of its resources. With respect to UDOT's Class 8 snowplow fleet, this philosophy has resulted in a reluctance to make remedial repair investments in equipment that was near or beyond its target replacement criteria. While understandable, the cumulative effect of this decision pattern is that a significant volume of undocumented maintenance backlog exists for older units, a position that is supported by the low volume of maintenance records for these vehicles, our random observation of units during our onsite visits, and the low auction prices received for this equipment.

Model Description

The AMA team's Class 8 snowplow fleet total asset cost model is contained the spreadsheet, "Model Age – sum by year – final.xls" (the Lifecycle Model). The primary data sources and key supporting analyses for this spreadsheet care ars follows:

1. "Class 8 Lifecycle.xls." This UDOT-provided spreadsheet contained a summary of vehicle usage and maintenance and repairs costs, organized by equipment number and the calendar month/year in which these costs and data were recorded. The source data for this spreadsheet was UDOT's Fleet Management System (FMS) from which UDOT personnel extracted this information. This data represented the base information the AMA team used its analysis of vehicle usage and maintenance and repairs costs patterns.

2. "Model Age – sum by year." Using the base information provided by UDOT (see above), the AMA consultants proceeded with four (4) iterative efforts of aggregating the "Class 8 Lifecycle" cost data that included exploring differing options for measuring unit costs, time/age, and mileage calculations. Ultimately, the AMA consultants settled on the following key decisions, which were incorporated into the Lifecycle Model Design:

    a. 'Age' was identified as the primary unit measure in the Lifecycle model. Driving this decision was the dominance of a seasonable usage pattern.

b. Age calculations are based on subtracting the vehicle's model year from the current year (e.g., a 2000 model year truck in calendar year 2015 would be 15 years old). Supporting this approach was a higher measure of data correlation (R^2 value[19]) when using this method as opposed to using in-service year as basis for determining vehicle age.

c. Information is presented on a yearly basis (i.e., the data is aggregated into calendar years); again this position is based on equipment usage patterns that do not support performing month-by-month analysis of costs.

d. "Actual" (recorded) mileage information is used as the basis for calculating utilization rather than miles based on fuel consumption records. In this case, while the use of calculated mileage based on fuel consumption records actually resulted in a marginally higher data correlation, the additional accuracy was offset by the added complexity.

3. "Auction Prices.xls." This spreadsheet is derived from a UDOT-provided spreadsheet titled, "Surplus Trucks 06-15-15," which contained the records of UDOT Class 8 Snowplow Truck sales for the years 2005 through 2014 (213 sales from 2005 to current, which includes three (3) sales in 2015). The results of this analysis providing a solid basis for establishing residual values for vehicle ages covered by the auction data. However, because nearly all records involved units that were 10 years or older in age, the ability to extrapolate this information to earlier years was not supported by the data.

Equipment Preventive Maintenance and Repair Costs (PM and Repair)

The following three (3) charts[20] are derived from PM and Repair cost data from the UDOT Class 8 snowplow truck fleet. The charts provide the base information for the Operating and Repairs cost used in our lifecycle model.

Figure 2 (below) identifies the annual average PM and Repair for the UDOT Class 8 snowplow fleet. Years 1-10 use UDOT's actual costs. For years 11 and beyond we use projected costs based on the identified trend line formula due to the significantly lower volume of records for equipment at these ages and the associated variance of UDOT data for these years. As identified on the trend line, the data for year 1-10 is very highly correlated (as measured by an R^2 value of 0.9842), indicating this pattern has a high degree of predictive reliability.

[19] R-squared is a statistical measure of how dose data fits a regression line

[20] From the "Model Age – sum by year – final.xls" spreadsheet.

Figure 2: UDOT Class 8 Snowplow PM and Repair Costs

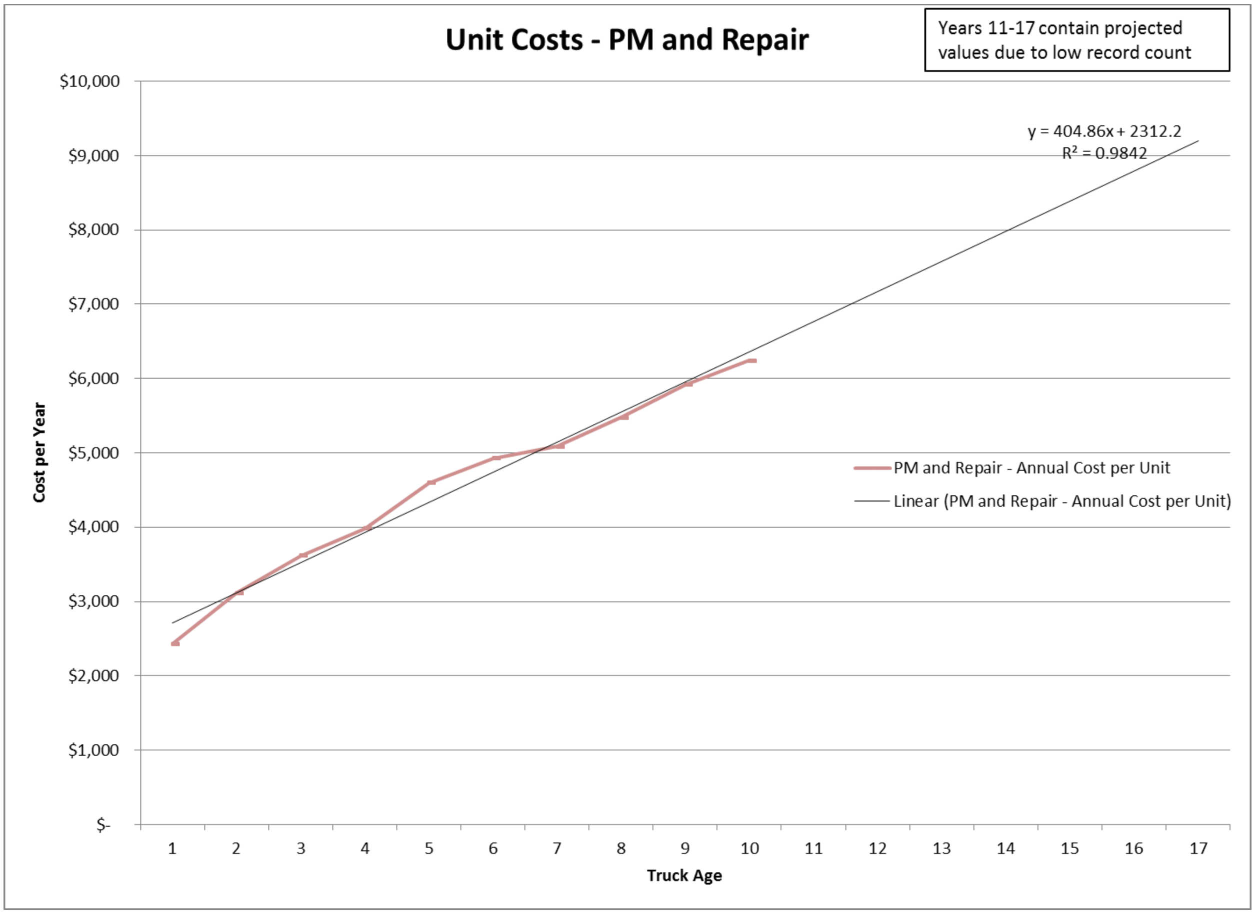
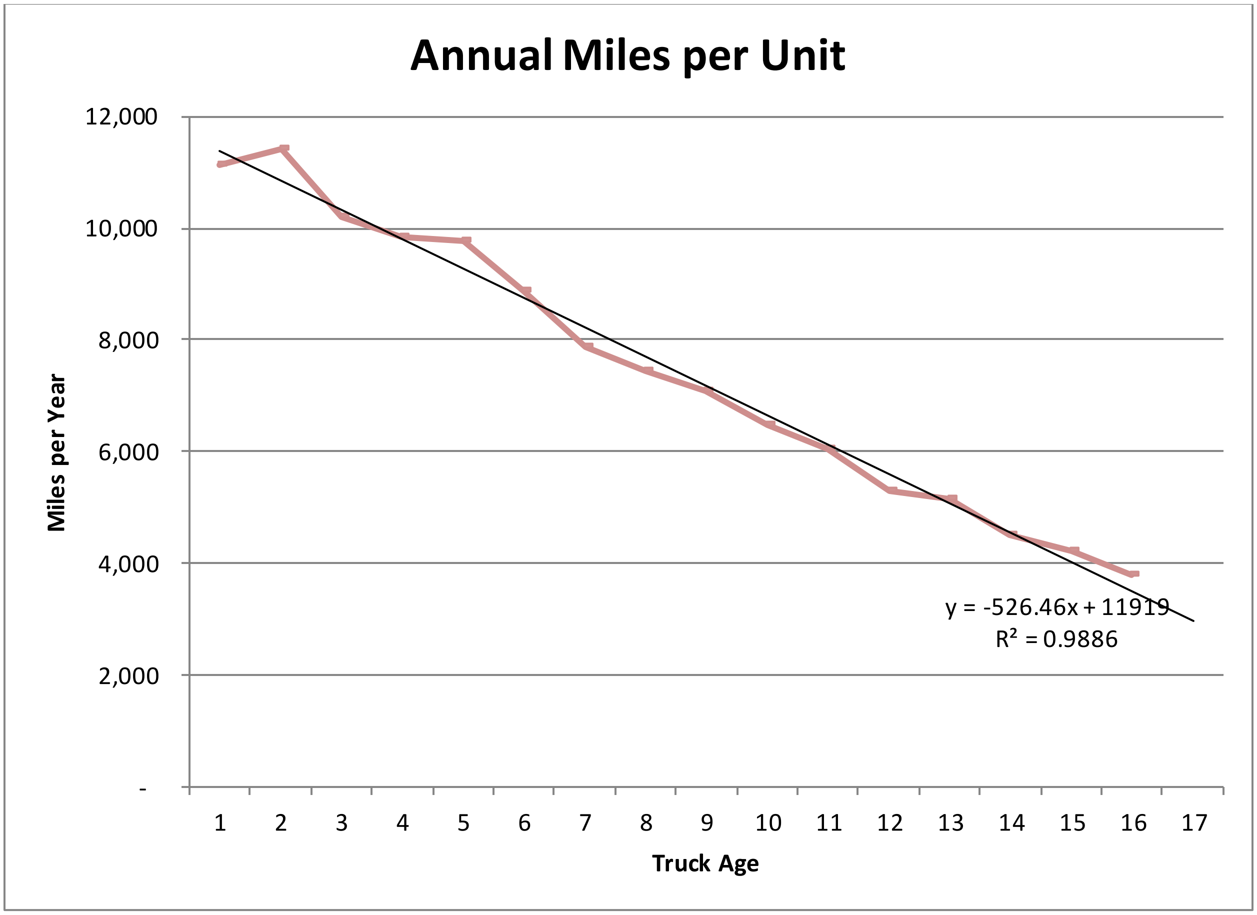


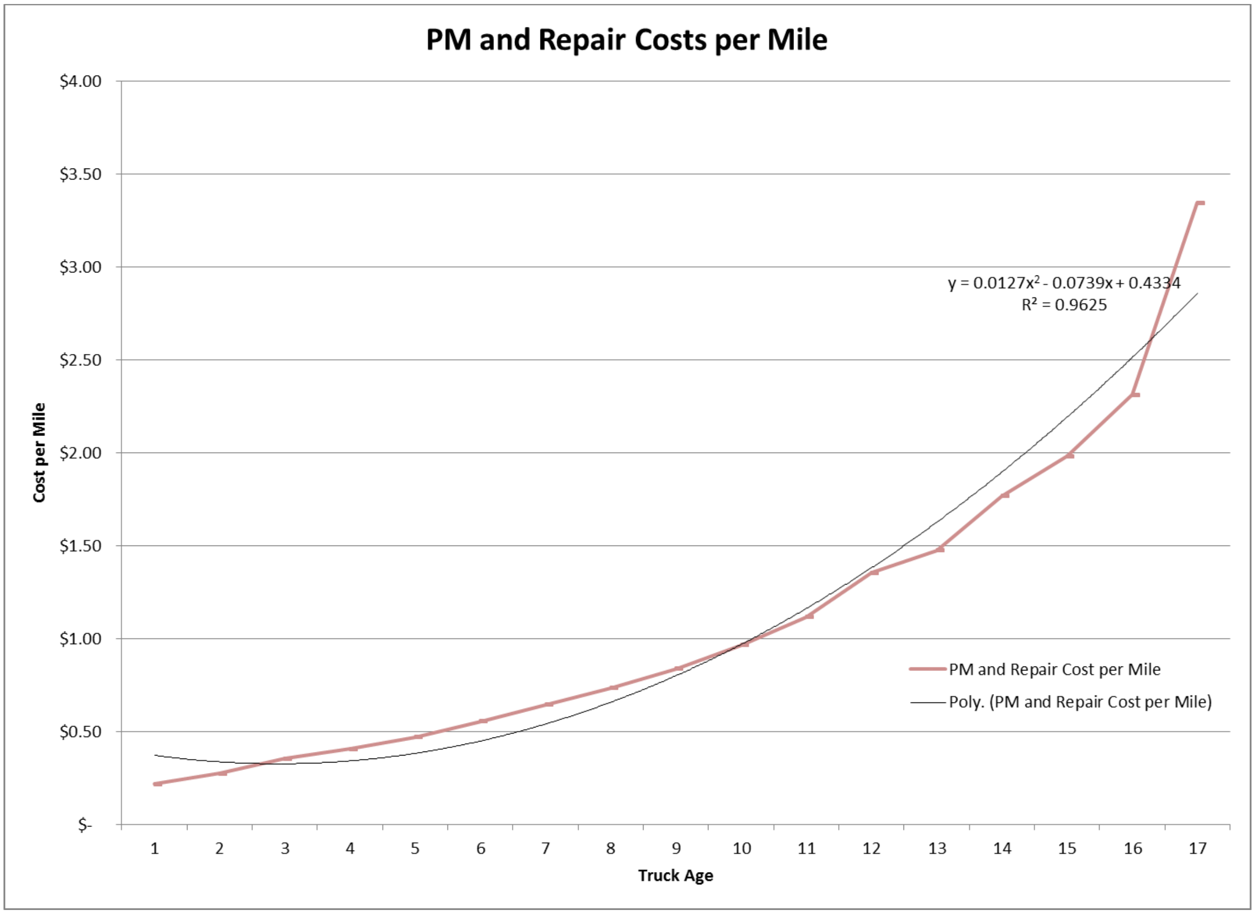
Figure 3: UDOT Class 8 Snowplow Truck Utilization per Year (below) is consistent with the typical utilization pattern for fleets although specifics clearly vary by client, application and vehicle type. Actual UDOT data is used for years 1-16 use while year 17 reflects a projected value. (As with Figure 2, the relatively low number of records available and the associated data variance supports using a projected value). Also as with Figure 2, the data for year 1-16 is very highly correlated (as measured by an R^2 value of 0.9886), indicating this pattern has a high degree of predictive reliability.

Figure 3: UDOT Class 8 Snowplow Truck Utilization per Year



In combination, the information presented in the above charts translates into Figure 4, which is a graphic presentation of UDOT's PM and Repair Costs per Mile:

Figure 4: UDOT Class 8 Snowplow Truck PM and Repair Costs per Mile



Again, we acknowledge that the PM and Repair Costs data from year 11-17 is based on cost projections while utilization for year 17 is also based of usage projections. However, these projections are highly correlated as demonstrated by a R^2 value of .9625, indicating a very high degree of predictive reliability.

Equipment Capital Costs

As described previously, the AMA team used the available records of UDOT auction prices of Class 8 snowplow trucks to establish a statistically supportable range of residual values for vehicles at age 10. Beyond that age, auction values continue to decline slowly but less predictably for reasons that are unclear but likely involve market demand at the time of sale and/or the actual vehicle condition. In combination, the AMA team identified a target residual value of $10,000 for a 10-year old UDOT Class 8 snowplow truck, followed by a $1,500 decline in value in year 11, $750 in year 12 and an additional $500 per year in subsequent years.

Given a lack of UDOT auction data on snowplow trucks less than 10-years old, the AMA team looked to other options for estimating residual value, the key information needed to plot the capital costs curve in the Lifecycle Model. Unfortunately, the following factors complicated this effort:

- Essentially no commercial 'marketplace' exists where a sufficient volume of Class 8 snowplow trucks are sold to establish a statistically valid range of residual values for UDOT-spec'd units. The following factors support this statement:

- The Class 8 snowplow trucks that UDOT operates are vehicles that are highly engineered to perform a single task – removing snow and performing other winter maintenance tasks as efficiently and effectively as possible.

- The demand for Class 8 snowplow trucks of the type used by UDOT is (nearly) exclusive to state DOT and/or municipal fleets that operate in heavy snow areas with severe terrain. As with most highly specialized equipment, the resale market for these vehicles is limited. In the case of the vehicles being studied, this market mostly consists of other public agencies with similar snow removal responsibilities or to firms/individuals that are willing to purchase a vehicle that may not be well-suited for general use, but may fit a particular service niche.

- Class 8 snowplow trucks of the type in this study have little/no value to the construction market. This is because when Class 8 trucks are specified for construction use, key considerations include maximizing hauling capacity while complying with highway weight limits. These factors encourage the use of lighter components and larger dump body capacities. In comparison, the Class 8 snowplow truck is considerably heavier that its construction use counterpart (with heavier front axles and supporting components to handle the additional weigh and stress of snowplows), has a smaller dump body, and is equipped with various snowplow mounting brackets, hydraulics controls, etc., all of which provide little to no benefit to contractors while adding to maintenance complexity and repair costs.

  While a commercial Class 8 construction-spec'd dump truck can be adapted to snowplow use, the predictable outcome would be a less capable vehicle that would be anticipated to require significantly more frequent repairs and additional maintenance in comparison to units specifically designed for snow removal and winter maintenance activities. Conversely, while a Class 8 snowplow unit can perform some level of general construction duties, it will be neither as cost-effective nor efficient as units designed for that task.

- The public entities contacted by our peer survey essentially represent the entire Rocky Mountain area market for Class 8 snowplow trucks. However, all the states contacted as part of the peer survey were selling similar Class 8 snowplow trucks at ages equal to or greater than UDOT, meaning that little or no data was available for providing residual value estimates for vehicles ages lower than those found in the UDOT auction records.

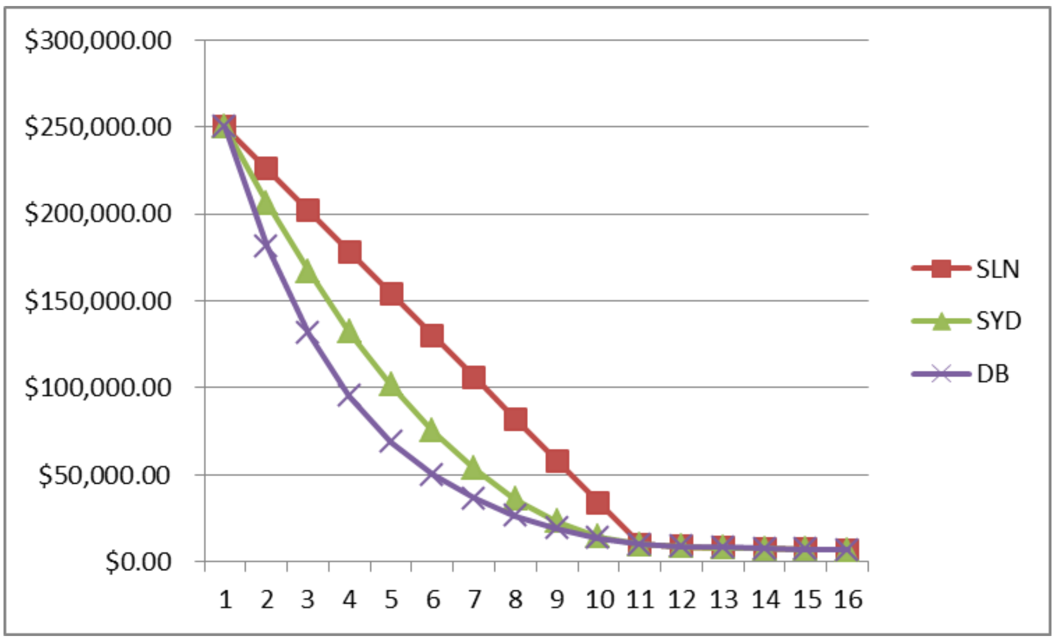
- While other DOTs such as Missouri, Minnesota, Michigan, or Pennsylvania operate Class 8 snowplows trucks (albeit, configured somewhat different from units operated in the Rocky Mountain region), vehicle sales prices for even commonly-available vehicles – cars, pick-ups, etc. - differ significantly by region. Accordingly, the Class 8 snowplow trucks prices received at disposal from DOTs distantly located to UDOT is perceived to have limited relevance to UDOT's 'residual value' question.

Lacking hard data to use in estimating equipment residual values during the early years of ownership, the AMA consultants considered what logical proxies existed for estimating residual equipment values. After reviewing the available research, the AMA ultimately determined that financial depreciation models could be adapted to this purpose and provided the additional benefits or familiarity and ease of use.

The AMA team notes that 'depreciation' is inherently an accounting/finance concept, with the choice of the technique used by a given entity typically determined by taxation and other considerations that have little relevance to the actual residual value of an asset at a given point in time. Accordingly, while the AMA team reviewed three (3) depreciation models as a proxy for identifying target residual values, our actual selection of the recommended residual value model was based on the professional judgement of the AMA team as to how well the predicted model values mirrored 'typical' fleet residual value curves.

The three (3) depreciation models examined by the AMA team were: 1) straight line (SLN), 2) sum-of-the-years (SYD) and 3) declining balance (DB). Figure 5: Comparison of Depreciation Models contains a graphic illustration of the application of these three (3) approaches to predict the residual value of an asset that is worth $250,000 when placed into service but has a residual value of only $10,000 at year 10 (factors that roughly mirror the UDOT Class 8 snowplow fleet):

Figure 5: Comparison of Depreciation Models



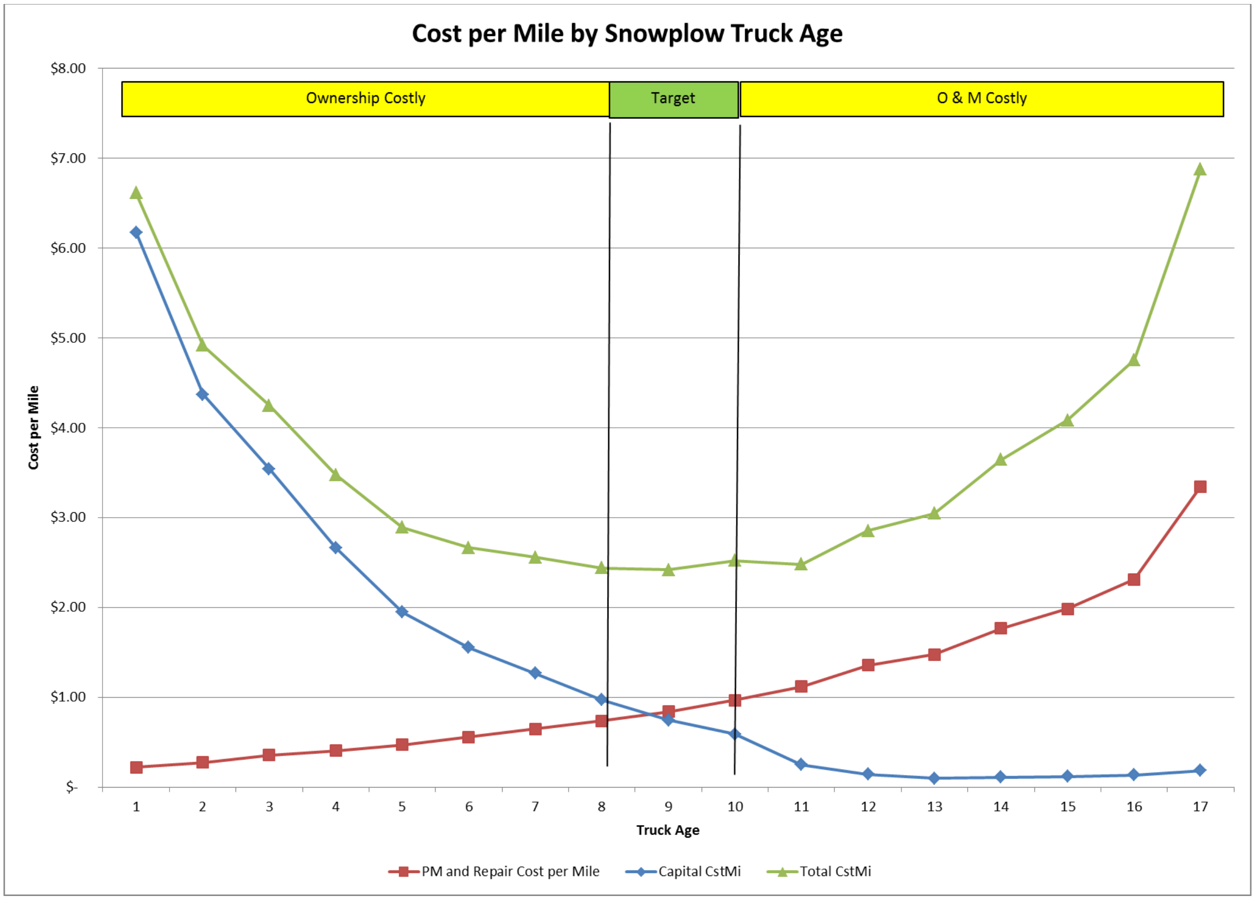
Of the three curves in this figure, the AMA team perceives the DB (declining balance) curve as the most intuitive when viewed within the context of the values for year 11 and beyond. In comparison, SLN (straight line) is non-intuitive for the same reason (the values in year 11 and beyond represent a distinct change from the trend in prior years). Finally, SYD (sum-of-the –years), while more supportable than straight line, projects significantly higher residual values for vehicles aged 4-7 than DB without any data to support those projections. Accordingly, the AMA team selected the declining balance depreciation model as a proxy for determining the capital cost values used in the lifecycle model while using the stated residual value assumptions (based on UDOT auction records) for vehicles aged ten (10) years and older at time of sale.

Note 6: The "Depreciation1" tab of the Lifecycle Model contains the data used to both create Figure 5 and to feed the Capital Cost data found in the Lifecycle Model.

Key Findings

Figure 6: Average Cost per Mile by Vehicle Age indicates UDOT's average cost of mile[21] by equipment age for its Class 8 Snowplow truck fleet:

Figure 6: Average Cost per Mile by Vehicle Age



As indicated above, the 'sweet spot' for this model is between years 8 and 10, with 9 years considered the target (ideal). The most powerful[22] factor determining this sweet spot is capital cost as these costs effectively dwarf maintenance and repair cost until the units reach year 9. Beyond year 9, preventive maintenance and repairs costs increase at progressively higher rates, consistent with the patterns for utilization and cost described previously in the *Minimizing Lifecycle Costs* section.

Recommendations

1. The AMA team recommends 9-years of age as the optimal replacement criteria for UDOT Class 8 snowplow trucks based on current fleet data and our Team's professional judgement. This recommendation provides the basis for our funding section that follows.

[21] Average Annual PM and Repair costs + Capital Costs by equipment age / by average miles driven by equipment age
[22] The model factor that provides with the strongest influence on the Total Asset Cost curve

2. The AMA team recommends adding a points-based equipment condition assessment process to aid UDOT in prioritizing units for replacement, creating a two-factor process for determining what equipment should be replaced.

With regards to the equipment assessment process, the AMA team recommends that UDOT modify its current annual inspection process to include the recommended vehicle condition evaluation system. The following is description of such a model:

"Evaluation Process for Fleet Vehicles

- A thorough inspection and operational check of each unit;
- An initial itemized list of repair/maintenance work for each vehicle;
- A general assessment rating using a standardized grading (alpha-numerical or defined
- term);
- A priority ranking for each item, for example: Critical, Urgent, Needed, Recommended;
- A detailed cost estimate for each vehicle;
- A determination of expected service life if repairs/rehab are done;
- A decision for the course of action for each unit of equipment (Routine Maintenance Only; Selective Repairs; Full Repair/Rehab; Defer and Re-evaluate within __ days; No Maintenance or Repair-Deadline; Remove from Fleet by Sale, Trade-In, Transfer)
- Final cost estimate based on evaluation"[23].

As described, this process offers a means for providing additional replacement priority to units that due to corrosion or overall condition (such as the current units with frame cracking issues), should be prioritized for replacement.

Other Fleet Replacement Criteria Considerations

The AMA team notes that in the literature review and peer survey, we identified a number of other replacement selection criteria besides those recommended (i.e., age and condition score) including mileage and life-to-date maintenance and repair costs (among others). However, the AMA team does not recommend adding additional criteria to the Class 8 snowplow trucks replacement criteria for the following reasons:

- Using accumulated mileage is a problematic replacement criterion for UDOT as UDOT's Class 8 snowplow trucks are used nearly exclusively for winter maintenance activities. Driving this fact is UDOT's compliance with the direction provided by its elected officials to contract the majority of its summer maintenance work program. In practice, the UDOT personnel that operate the snowplow trucks during winter maintenance activities are involved with activities not supported by snowplow truck usage during the summer (such as construction inspection and similar activities where light duty vehicles are much more appropriate and much less costly to operate). In contrast, many state DOTs directly perform a significant volume of the summer maintenance program, using their snowplow trucks to haul gravel, sand and asphalt (as required) making accumulated mileage a more valuable replacement criterion.

- The use of Life-To-Date maintenance and repair expenditures as a replacement criterion only makes sense to the extent that a pattern of past repair expenditures is predictive of continued repair costs. As a practical matter, a unit with a significant level of repair costs could be indicative of a unit that is

[23] Nazari, M., Bergner, D., Shi, X., "Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment used by Transportation Agencies for Snow and Ice Control", Western Transportation Institute, Montana State University, April 2015, page 50.

in better-than-average condition due to having repairs performed. In practice, the AMA team simply perceives that the recommended points-based evaluation criterion is a much more logical means of identifying units for which replacement is the preferred option than a simple accumulation of costs.

- As described in the Oregon study[24], age is the most powerful predictor in terms of identifying equipment replacement priorities to achieve the lowest lifecycle cost. Beyond that, the Oregon study indicated that the ability to leverage additional inputs for improving the prediction accuracy is much more dependent on the availability and accuracy of equipment cost data. Accordingly, the AMA team perceives the recommended approach as superior to adding any replacement factors without any direct support of achieving a preferable outcome.

Other Comments of the Lifecycle Model and Data

Finally, the AMA team recommends that UDOT periodically revisit its Class 8 fleet lifecycle replacement criteria to address the following concerns:

- Evolving emission regulations are changing the cost and service profiles of Class8 snowplow trucks (as well as other UDOT equipment).
- Corrosion damage remains an ongoing concern associated with the expanded use of ice and snow treatment chemicals. While 'best practice' guidance exists with respect to equipment specification and maintenance practices[25], the success of these practices in restoring/extending equipment lifespans remains a question within the context of a given fleet related to the near infinite number of potential, local variables (e.g., the quality of post application equipment cleaning practices, use of recommended remedial treatments, etc.).
- UDOT's existing Class 8 snowplow truck maintenance and repair data includes a significant volume of corrosion-related repairs. Currently, corrosion repairs are not categorized in a way that allows distinguishing these costs from other maintenance and repair costs. To segregate and identify these corrosion costs, UDOT will need to adjust its repair coding practices. Even so, it will take several years of data capture to distinguish these costs and determine what changes, if any, are needed to adjust the equipment replacement criteria to reflect the impacts of ice and snow treatment chemicals.
- To extent that specification changes and revised operator cleaning and other maintenance practice changes alter Class 8 snowplow cost patterns, UDOT will need to reexamine the new data to determine whether any adjustments are needed to the replacement criteria.

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[24] Kim, D.S., et al., Fleet Replacement Modeling: Final Report, SPR 670, Oregon Department of Transportation and Federal Highway Administration, Salem, 2009 [Online]. Available: http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2009/Fleet_Model.pdf?ga=t .

[25] Nazari, M., Bergner, D., Shi, X., "Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment used by Transportation Agencies for Snow and Ice Control", Western Transportation Institute, Montana State University, April 2015.

Funding

Expenditure Projection Summary

Utilizing the nine (9) year optimal replacement criteria calculated as part of the life-cycle costing analysis, the AMA team developed a series of replacement projections to determine the impact of the age criteria on expenditure requirements and the average age of the fleet. The replacement projection scenarios included three separate analyses:

- Achieve an overall average fleet age of 9 years or under in 3 years and an average fleet age of 4.5 years within 9 years (this is referred to as the most aggressive plan)
- Achieve an overall average fleet age of 9 years or under in 4 years and an average fleet age of 4.5 years within 9 years (this is referred to as the moderate plan)
- Achieve an overall average fleet age of 9 years or under in 5 years and an average fleet age of 4.5 years within 9 years (this is referred to as the least aggressive plan)

In order to determine when a vehicle was due for replacement, the replacement criterion of 9 years (or 108 months) was applied to the age of the vehicle (determined by subtracting the model year from the current year). The projected replacement cost was determined by establishing a current year baseline cost of $225,000. This cost was then inflated at a rate of 3 percent annually to establish out year cost projections. This approach provided an annual replacement requirement in terms of both unit counts and replacement expenditures.

A critical first step in the development of an asset replacement strategy is the establishment of the baseline scenario given the existing fleet of assets and the desired replacement criteria. In order to create a baseline scenario for UDOT the AMA team applied the desired nine (9) year replacement criteria as determined by the lifecycle costing model to the current inventory of assets. The usefulness of this baseline is that it provides a number of indicators as to the feasibility of immediately transitioning to the calculated replacement criteria, including:

- The proportion of the fleet that is already at or beyond the desired replacement criteria (known as "the backlog")
- The project expenditure requirements to bring the fleet into compliance with the desired replacement criteria
- The reasonableness of the expenditure plan as a possible implementation strategy.

It is clear from the average fleet age data that UDOT will have a substantial backlog of replacement requirements. Based on the established 9 year desired replacement criteria, approximately 69 percent of the fleet is due or overdue for replacement. Given that there is no reasonable way to acquire and/or in-service 69 percent of the fleet in a single year, an analysis was conducted in order to distribute this backlog of replacement over the initial 3, 4, or 5 years of the plan as described above.

This distribution process allows for the establishment of a set of replacement projections that are more reasonable in terms of both financial and operational practicalities. Table 2: Funding Need Projections (below) summarizes the number of units that would be replaced in each given year based on the optimal 9-year replacement cycle.

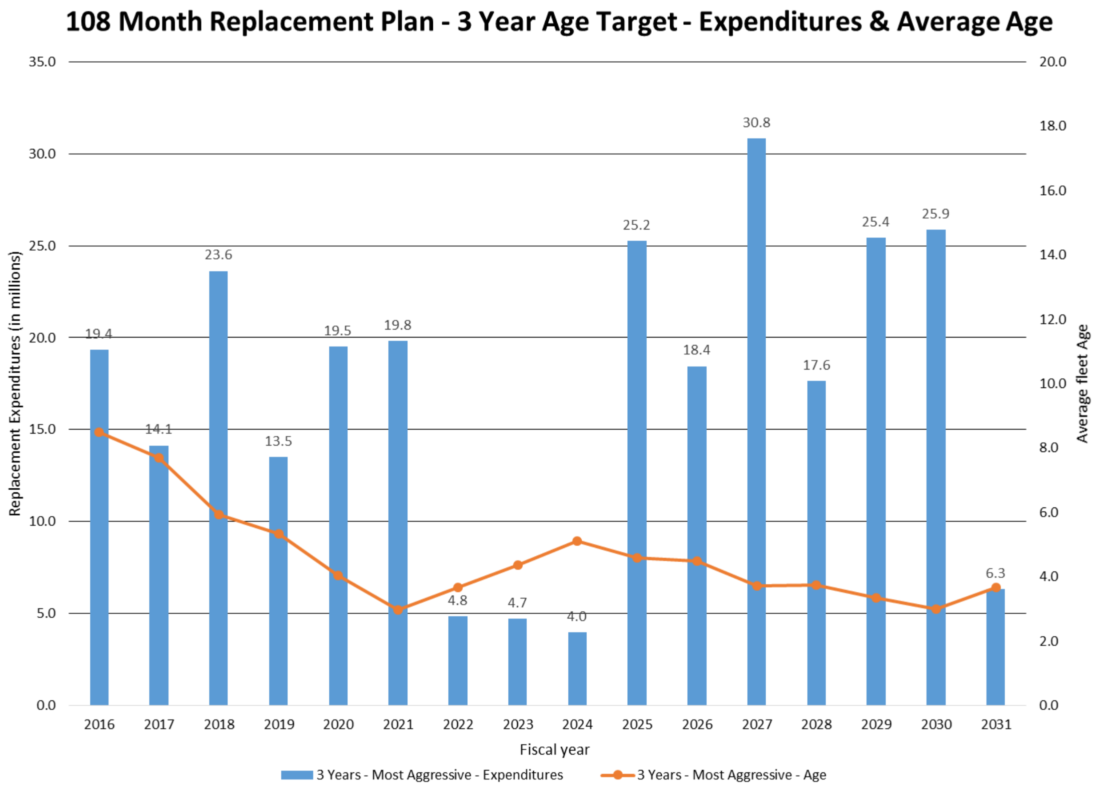
Table 2: Funding Need Projections

	Baseline	5-year plan	4-year plan	3-year plan
2016	345	49	66	86
2017	20	52	64	61
2018	39	61	65	99

	Baseline	5-year plan	4-year plan	3-year plan
2019	16	58	66	55
2020	16	52	69	77
2021	18	58	50	76
2022	18	56	55	18
2023	17	55	54	17
2024	14	56	14	14
2025	345	55	66	86
2026	20	52	64	61
2027	39	61	65	99
2028	16	58	66	55
2029	16	52	69	77
2030	18	58	50	76
2031	18	56	55	18

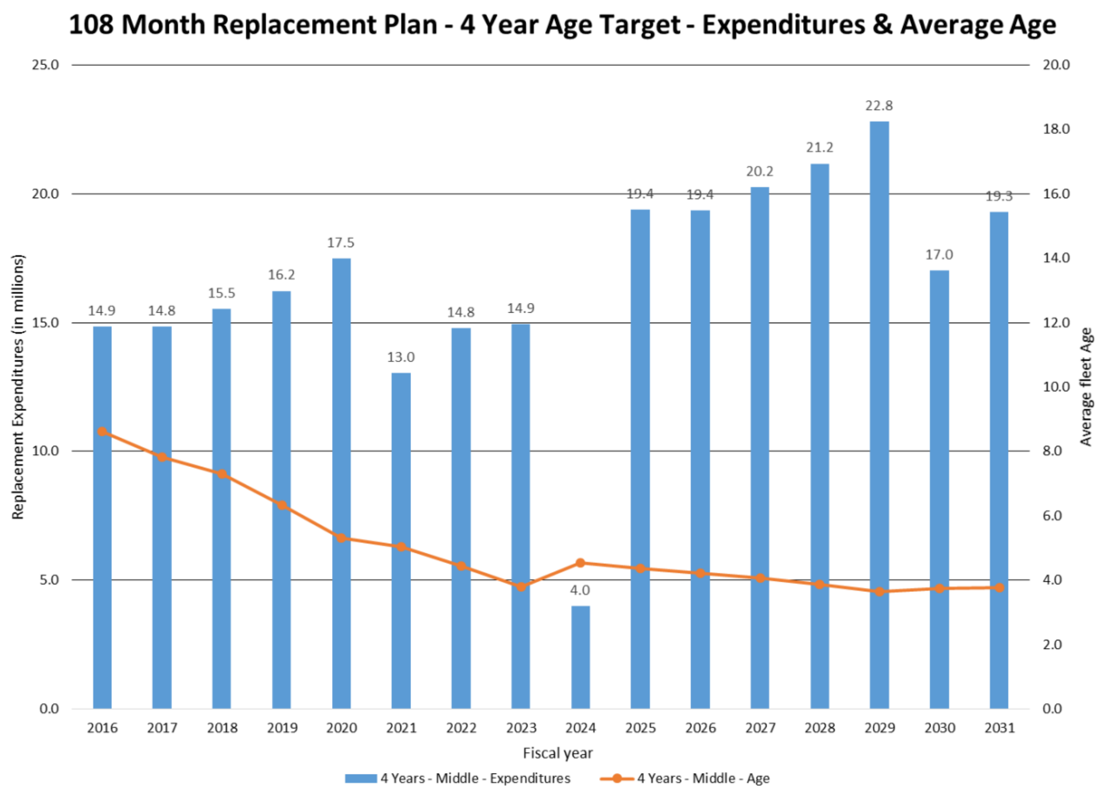
When comparing the plans it is important to keep a basic fact in mind; under idealized conditions the number of units to be replaced annually is simply the total unit count divided by the desired replacement criteria. Using a 503 vehicle inventory and a 9 year replacement criteria, it would be expected that UDOT would replace approximately 56 units per year (503 units /9 year cycle = 55.8). As is clear from the above table, the 3, 4, and 5 year plans generally achieve that with some degree of variability. The unit count projections provided in the above table serve as the base from which to develop expenditure requirements necessary to support each of these plans and the impact that each plan would have on the average age of the fleet.

In evaluating the most aggressive approach to replacement where the backlog is eliminated over a three year period, it is understandable that this plan would require the greatest level of expenditure in the early years but would also result in a rapid reduction in average fleet age. As can be seen in the chart below, the first three years of the plan would require approximately $57 million in expenditures and would result in reducing the average age from the current 10 to 6 by year 3 and would achieve the optimal average of 4.5 years old by year 4. The average fleet age then floats with the number of units replaced annually ranging from 3 years in the sixth year of the plan to 5.8 years in the ninth year of the plan.



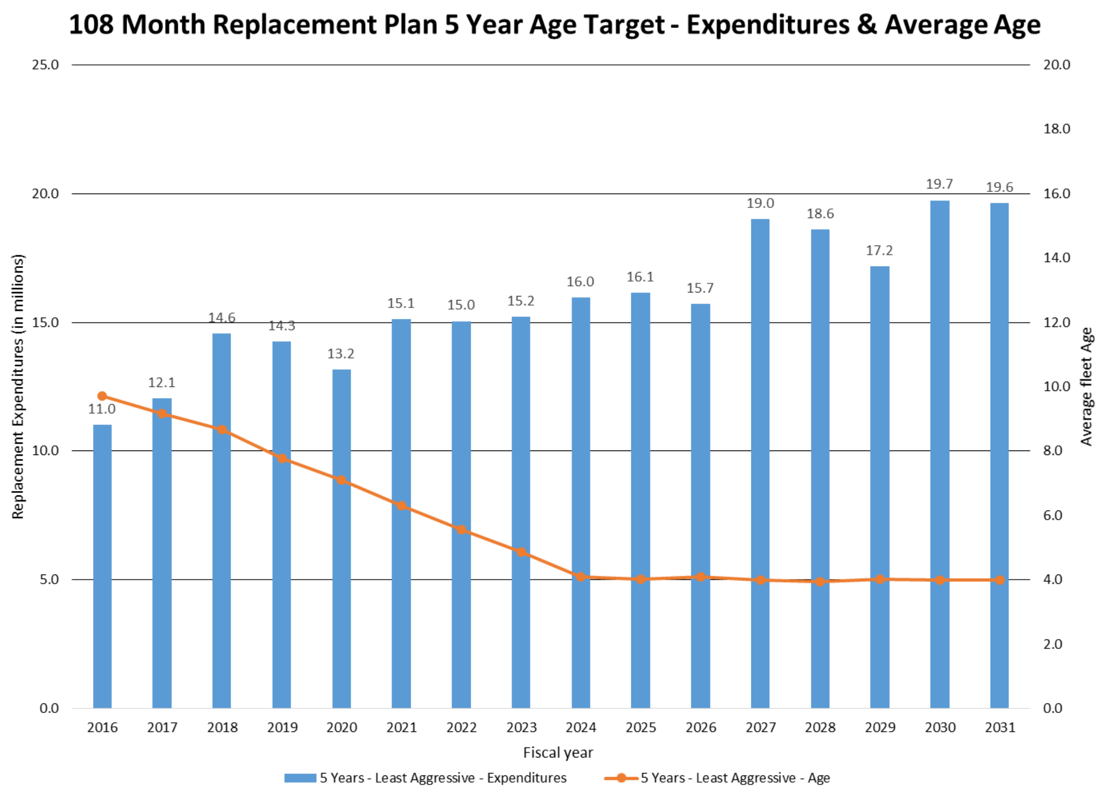
NOTE 8: Due to the design of the funding model, fleet 'average age' appears on graph as 4 years but the actual value is 4.5

The primary negative of the 3-year plan is that the annual expenditure requirements remain volatile and results in continued volatility in fleet age over the horizon of the plan. To address this, further smoothing of the backlog was done in the 4 and 5 year versions. As would be expected, distributing the backlog over 4 years instead of three reduces the total expenditures required and it also requires a slightly longer period to reduce the average age of the fleet. A total of $45.2 million in expenditures are required in the first 3 years and the optimal average age is not achieved until the seventh year of the plan. However, the more limited volatility in annual replacement expenditures ensures that once the fleet achieves that optimal age it remains much closer to that value (i.e., the flatter red line).



NOTE 9: Due to the design of the funding model, fleet 'average age' appears on graph as 4 years but the actual value is 4.5

The last iteration of the analysis distributed the backlog over a 5 year period. In this iteration the expenditure requirement of the initial 3 years of the plan is $37.7 million. This approach achieves the optimal age in the ninth year of the plan and results in a much steadier reduction. As with the 4 year plan, once the optimal average age is achieved it hardly varies over the remaining 6 years of the plan due to the consistency of the number of units being replaced on an annual basis.



NOTE 10: Due to the design of the funding model, fleet 'average age' appears on graph as 4 years but the actual value is 4.5

Comparative Comments

The 3 year and 5 year plans offer the best alternatives for UDOT. Over the first 9 years of the plans, the 3 year option requires $123 million in expenditures while the 5 year plan requires $125 million. The 3 year plan also allows the average age of the fleet to reach the optimal point sooner than the 5 year plan. While these benefits would appear to indicate that the 3 year plan is the most feasible option, there are key characteristics of the 5 year option that make it compelling as the chosen option.

A highly compelling aspect of the 5 year plan is the comparative consistency of the annual expenditure requirements. The regularity of the budgetary requirements comports well with the nature of public sector revenues. This consistency makes it more likely the State will be able to comply with the plan since the maximum variability over the 15 year term of the plan is $8 million.

A second compelling element of the 5 year plan is a derivative of the consistency of the projected expenditure requirements. The gradual reduction in fleet age and the limited variability of the average age in the out years of the plan would allow UDOT to transition its maintenance services to support a comparatively new fleet in a more deliberate manner and would allow for continued compliance with that approach over the long term. For example, if it is determined that services for this component of the fleet should focus primarily on preventive maintenance services and light repairs given the decrease in average age. If this is the case, it will be important to ensure that no vehicle ages to the point where it requires substantial repair efforts UDOT will have transitioned away from having the appropriate resources to provide those kinds of services.

These characteristics make the 5 year option a more reasonable and feasible option for UDOT. The number of units replaced in the early years of the plan would support the elimination of units that are susceptible to the frame cracking issue while also supporting the renewal of the fleet.

Recommendation

UDOT should seek the necessary support to pursue the 9-year replacement cycle of a 5-year term Target Plan described above.

The AMA team's understanding is that a major constraint with executing the recommended strategy is that the Utah Legislature has line-item budget control over the amount of UDOT's annual maintenance budget that can be spend to purchase equipment, currently identified as $6.3M[26]. This is approximately 50% the annual requirements of approximately $13 million per year over the first 5 years of the plan. As described and detailed in the Lifecycle Costing Model section, only by adhering with the recommended Class 8 snowplow replacement schedule can UDOT and the State's achieve the lowest total cost for its taxpayers. Otherwise, simply restricting the funds UDOT can spend on new equipment will predictably increase the funds it spends in other budget categories. Most importantly, UDOT's ability to deliver on its core mission of "Keeping Utah Moving" is best supported by the recommended strategy as only by having an optimal age fleet can UDOT ensure that it has the actual capacity to deliver its winter maintenance program at the targeted levels of service.

[26] Slide 16 from UDOT-produced "Area Supervisor Workshop April 2015" PowerPoint presentation.

Appendix A: Literature Review Citations

STUDIES ON STATE DOT EQUIPMENT REPLACEMENT AND FUNDING PRACTICES

1. Lauria, P and Lauria, D., NCHRP Synthesis 452, "State Department of Transportation Fleet Replacement Management Practices," 2014 [Online]. Available: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_452.pdf

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2. Fan, W., et al., Equipment Replacement Optimization, Research and Technology Implementation Office, Texas Department of Transportation, Austin, FHWA/TX-11/0-6412-1, 2011 [Online]. Available: http://www.utexas.edu/research/ctr/pdf_reports/0_6412_1.pdf 2011.
3. Gillespie, J.S. and A.S. Hyde, The Replace/Repair Decision for Heavy Equipment, Virginia Transportation Research Council, Charlottesville, 2004 [Online]. Available: http://www.virginiadot.org/VTRC/main/online_reports/pdf/05-r8.pdf.
4. Hildreth, J., "Modeling Equipment Costs," presentation to 2012 National Equipment Fleet Management Conference, June 2012.
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6. Kriett, P.O., W.N. Mbugua, D.S. Kim, and J.D. Porter, "Equipment Replacement at Departments of Transportation: Prioritization Measures, Software Tools, and Supplementary Data," Transportation Research Record: Journal of the Transportation Research Board, No. 2150, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 10–15.
7. Vorster, M. , "Fleet Age Planning", presentation to 2012 National Equipment Fleet Management Conference, June 2012.
8. Weissmann, J. and A.J. Weissmann, "Computerized Equipment Replacement Methodology," Transportation Research Record: Journal of the Transportation Research Board, No. 1824, Transportation Research Board of the National Academies, Washington, D.C.,2003, pp. 77–83.

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9. CTC & Associates, LLC, Preliminary Investigation: National Survey of Equipment Management Practices, Caltrans Division of Research and Innovation, Sacramento,2012 [Online]. Available: http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/equipment_management_national_practices_-_preliminary_investigation_2012-06-07.pdf.
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11. Lauria, P.T., Challenges and Opportunities: A Strategic Plan For Equipment Management Research, NCHRP Project 20-7/Task 309, 2011 [Online]. Available: http://maintenance.transportation.org/Documents/NCHRP%2020-7,%20Task%20309,%20Final%20Final%20Report-October%202011.pdf.

REPORTS ON CORROSION PREVENTION PRACTICES

12. "Equipment Corrosion," Washington State Department of Transportation, presentation to the APWA & PNS North American Snow, April 2011.

13. Nazari, M., Bergner, D., Shi, X., "Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment used by Transportation Agencies for Snow and Ice Control", Western Transportation Institute, Montana State University, April 2015.

14. Shi, X., Hansen, G., Jungwirth, S., "Preserving the Value of Highway Maintenance Equipment against Preserving the Value of against Roadway Deicers: Case Study and Cost Benefit Analysis Roadway Deicers: Case Study and Cost Benefit Analysis," presentation at the TRB 2014 Annual Meeting.

15. Yongxin L.; Shi, X.; Jungwirth, S.; Seeley, N.; Fang, Y., "Corrosion Inhibitors Available for Preserving the Value of Equipment Asset in Chloride-laden Environments: State of the Knowledge," presentation at the TRB 2014 Annual Meeting.